Prospects for Development of Fusion-Fission Hybrid Reactor (FFHR) in Korea

Doo-Hee Chang*
Nuclear Fusion Technology Development Division, Korea Atomic Energy Research Institute, Daejeon 34057, Korea
**Corresponding author: doochang@kaeri.re.kr*

1. Introduction

A fusion-fission hybrid reactor (FFHR) is a fusion reactor surrounded by a fission blanket, containing the Thorium, Uranium, and TRU elements, to increase output power, to breed fissile fuels, and to incinerate (transmute) radioactive materials [1]. The technological experience and challenge for the operation of experimental fusion reactors, such as KSTAR and ITER [2, 3], could be a background knowledge of fusion driver for the FFHRs in Korea. Furthermore, the commercial fission reactors, such as PWR and HWR [4], are being operated successfully during more than 40 years in Korea. Therefore, the development of an experimental test-FFHR, named a Proto-FFHR, can be suggested as an alternative and supporting device of future pure fusion reactors in Korea.

2. Background Study of FFHRs

The background studies and reviews of FFHRs are presented in this section. The most common hybrid design consists of a fusion reactor core surrounded by a blanket of fissile material such as Uranium or Thorium [5], as shown in Fig. 1. The generation of neutrons by the fusion of hydrogen isotopes in the core drives fission reactions in the fission blanket. These neutrons can be used to generate electricity, produce nuclear fuel for LWRs or transmute wastes.

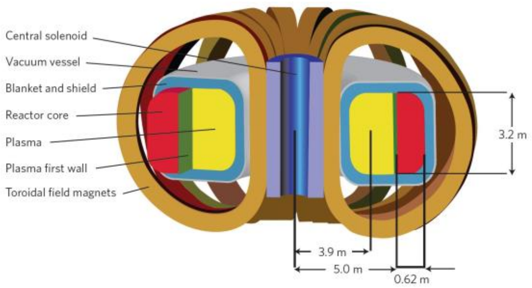


Fig. 1. The most common hybrid design.

For the fuel production of fission blanket, an absorption of the D-T fusion neutron in ^{238}U can result in formation of fissile ^{239}Pu via the reactions [1]

$$n + {}^{238}\mathrm{U} \rightarrow {}^{239}\mathrm{U} \xrightarrow[24\ \mathrm{min}]{\beta^-} {}^{239}\mathrm{Np} \xrightarrow[2.4d]{\beta^-} {}^{239}\mathrm{Pu} \quad \left[{}^{238}\mathrm{U}(n, \gamma + 2\beta^-){}^{239}\mathrm{Pu}\right]$$

where the symbols (n, γ) mean that a neutron is absorbed and a gamma ray is emitted; b indicates beta-decay (electron emission), and the 24 min and 2.4 days are the half-lives of the beta-decays. The fertile ^{232}Th can breed fissile ^{233}U by the reactions

$$n + {}^{232}\mathrm{Th} \rightarrow {}^{233}\mathrm{Th} \xrightarrow[22\ \mathrm{min}]{\beta^-} {}^{233}\mathrm{Pa} \xrightarrow[27d]{\beta^-} {}^{233}\mathrm{U} \quad \left[{}^{232}\mathrm{Th}(n, \gamma + 2\beta^-){}^{233}\mathrm{U}\right]$$

Although the amount of ^{235}U available is limited, the reserves of the fertile isotopes ^{238}U and ^{232}Th are vast, including spent fuel from fission reactors. High energy neutron sources are needed to cause this breeding. If the Np and Pa are not removed from the reactor, neutron capture can prevent their decays to ^{239}Pu and ^{233}U, thus reducing fissile fuel production.

2.1 Major Purpose of FFHR

There are four major purpose of FFHR development, as listed in the followings;

(a) Fuel supply, through a breeding process
(b) Electricity production
(c) Radioactive waste management, through a burning process
(d) High-energy volume neutron source, through the fusion reactions

2.2 Potential Advantages of FFHR

There are many potential advantages for the development requirement of FFHR, as listed in the followings [6];

(a) Lower requirement on plasma-related parameters
- Improved energy balance by fission blanket
- Q ~ 5 (Q $\gg$ 10 for pure fusion reactors)

(b) Rich neutrons to achieve multi-purposes (neutron multiplications)
- Improved neutron balance by fusion neutrons

(c) Good passive and inherent safety performances
- Subcritical reactor

(d) Avoidance of nuclear proliferation
- Large design margin by subcritical features

(e) Benefit both fusion and fission
- Fill in the gap, promote fusion, and solve left problems by fission

2.3 Special Characteristics of FFHRs

Some special characteristics of the FFHRs are summarized in the followings [7];

(1) Repositories
- Both pure fission or hybrids require repositories
- Fission byproducts, not actinides may be most dangerous
- Least expensive technical solution

- Very difficult politically (e.g. Yucca Mt.)

(2) Technical comparison of pure fission and fusion-fission hybrids
- Hybrids compare favorably to pure fission solutions (e.g., breeders and burners)
- Hybrids assume advances in technology: materials and new fuel forms
- Pure fission assumes existing technology

(3) Economic comparison of pure fission and fusion-fission hybrids
- General consensus for a single reactor is that
  $ LWR < $ Fast Reactor < $ Hybrid
- Fair comparison requires overall systems analysis
- Large number of LWRs + a few hybrids
- Small number of LWRs + a large number of breeders

(4) Proliferation
- Hybrids have significant quantities of fissile materials
- Proliferation risk much greater than for a pure fusion reactor
- Proliferation risk comparable to a pure fission reactor
- Substantial variation depending on design and fuel cycle

(5) Comparison of pure fission with hybrids
- The most important near term problem
- Compare, at a basic systems level, various hybrid concepts with comparable fission solutions
- This must done in a fair way
- Comparable assumptions for both
- Hybrids using fission assumptions
- Fission using hybrid assumptions

(6) Fusion technology
- Fusion technology program (KSTAR and ITER projects) has been started
- We will be able to make hybrids or pure fusion in 50 years if we continue the technology developments
- Of particular importance is materials research (need for long-term irradiation researches), including neutronics (need for high-flux neutron researches)

2.4 Comparison of FFHRs with LMFBRs

The potential benefits of hybrid reactors relative to the conventional liquid-metal fast breeder reactors (LMFBRs) are summarized in the followings [1];

(1) Potential advantages relative to LMFBRs
- No fissile fuel is needed for startup
- Time required to breed enough fissile fuel to start up a new fission reactor is shorter than LMFBRs
- One hybrid can provide fuel for many fission reactors
- Hybrid blanket power density is lower than LMFBR, so fuel element design is easier
- Hybrids have less afterheat, so a loss of coolant accident (LOCA) is less severe
- Hybrids may have lower fission product inventories and lower fissile fuel inventories
- Hybrids can also accelerate the development of pure fusion power

(2) Potential disadvantage relative to LMFBRs
- Hybrids are less developed; costs are uncertain
- Hybrids, because they are fusion reactors, have large tritium-handing requirements
- Fusion reactor design is more complex than LMFBR, and maintenance is more difficult
- Power core has to accommodate 14 MeV neutrons for long duration operational periods

2.5 Power Flow of FFHR

In developing the figures of merit for the hybrid, it is illuminating to describe the performance of the hybrid in terms of the power flow, as shown in Fig. 1 [8].

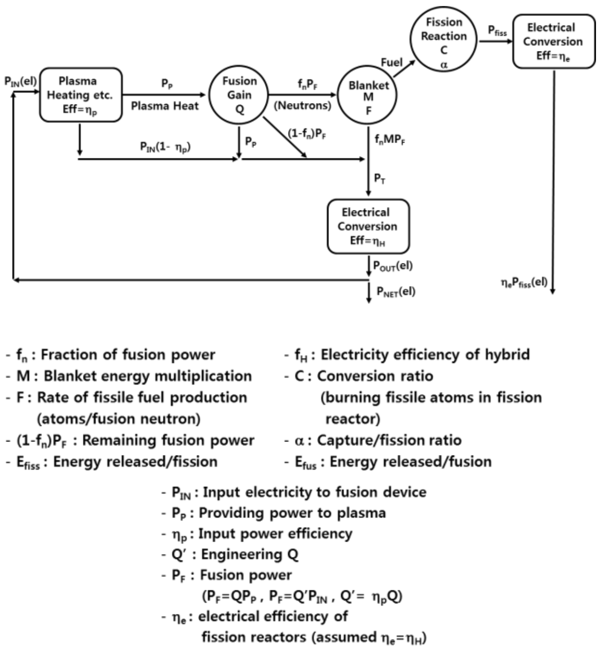


Fig. 2. Diagram and definition of the power flow and for a fission-fusion hybrid device producing the makeup required for a number of fission reactors.

- Total thermal power

$$P_T = P_{IN} + (1-f_n)P_F + f_nMP_F = P_F[1/Q' + 1 + f_n(M-1)]$$

- Overall electrical efficiency of hybrid

$$\eta_{HB} = \frac{\eta_H P_T - P_{IN}}{P_T} = \eta_H - \frac{1/Q'}{[1/Q' + 1 + fn(M-1)]}$$

- Energy, released in consumption of one fissile atom (net), in fission reactors

$$\frac{E_{fiss}}{(1-C)(1+\alpha)}$$

- Fusion energy, released in production of one fissile atom, in hybrid

$$\frac{E_{fus}}{F}$$

- Ratio of fission to fusion power

$$\frac{P_{fiss}}{P_F} = \frac{E_{fiss}}{E_{fus}} \times \frac{1}{(1-c)(1+\alpha)}$$

- Number (N) of fission reactors, supported by a hybrid of the same thermal power

$$N = \frac{P_{fiss}}{P_T} = \frac{E_{fiss}}{E_{fus}} \times \frac{F}{[1/Q'+1+fn(M-1)]} \times \frac{1}{(1-c)(1+\alpha)}$$

- Ratio of Total Electrical Capacity of System to Fusion Power

$$P_{el} = (P_{NET} + \eta_e P_{fiss})/P_F = \frac{\eta_{HB} P_T}{P_F} + \frac{\eta_e P_{fiss}}{P_F}$$

- Thermal Power Ratio

$$R = \frac{R_{el}}{\eta_H} = \frac{\eta_{HB}}{\eta_H} \times \frac{P_T}{P_F} + \frac{P_{fiss}}{P_F} = \frac{\eta_{HB}}{\eta_H} \times \frac{P_T}{P_F} + R_o$$

Where R: Appropriate ratio for on-line operation of hybrid

R_o: Appropriate ratio for off-line operation of hybrid

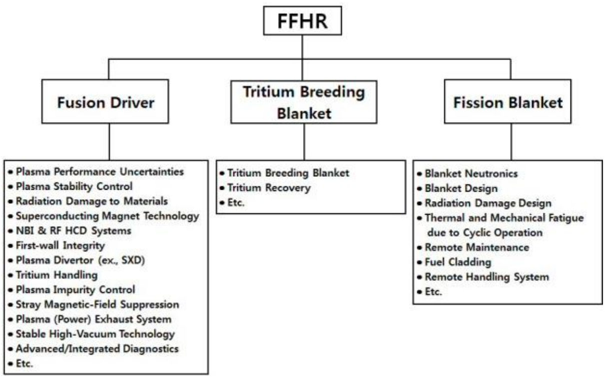
- From above equations,

$$R_o = \frac{E_{fiss}}{E_{fus}} \times \frac{1}{(1-c)(1+\alpha)} \quad \text{and} \quad R = \frac{1}{Q'}\left(1 - \frac{1}{\eta_H}\right) + 1 + f_n(M-1) + R_o$$

To best realize the potential advantages of the hybrid system, we need to maximize the parameters, η_{HB}, N, R (or R_o). If off-line operation of the hybrid is the preferred node of operation, then the parameter η_{HB} is not particularly important provided that $\eta_{HB} > 0$.

2.6 Key Technologies of FFHRs

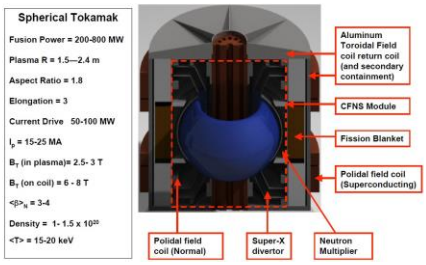
The key technologies of FFHR is summarized in the following diagram [9];



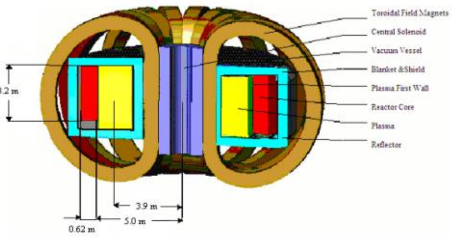
3. Major International Activities toward FFHRs

3.1 USA

The US hybrid research follows the trends of fission reactor. The fissile fuel availability was a major concern, and then US hybrid studies almost exclusively considered the breeding process in 1970s ~ 1980s [10]. An environmental consideration was entered in 1990s ~ 2000s. The US hybrid studies in this era strongly emphasize the fission waste destruction. Thus, both breeding and waste destruction may become a very important point of US hybrid research.



(a)



(b)

Fig. 3. Preliminary designs of (a) UT-Compact Fusion Neutron Source (CFNS)-Hybrid and (b) Subcritical Advanced Burner Reactor (SABR)-Jeorgia Tech.

3.2 Russia

The R&D program for hybrid systems and enabling technologies will be realized with the following milestones in Russia [11]:

(a) Design and construction of the demonstration fusion neutron source DEMO-FNS (fusion neutron source) on the basis of a superconducting tokamak for tests of SSO (steady-state operation), hybrid blankets and nuclear technologies by 2023;

(b) Design and construction of the pilot hybrid plant (PHP) by 2030.

Creation of DEMO-FNS and PHP accompanied by the progress of hybrid technologies will make a significant input into the nuclear technologies of the new generation through the development of structural materials for the first wall and blanket of hybrid and fusion power plants as well as for technological systems providing a SSO of thermonuclear plasmas, diagnostics, tritium breeding blankets, control systems, etc. Additionally, the issues of the lifetime extension and the duty factor enhancement will be addressed and basically solved for irradiated components of hybrid systems.

Development of FFHS (fusion–fission hybrid systems) together with realization of the ITER project should provide the basis for pure fusion DEMO and commercial fusion power plant construction in Russia by 2050.

R (m)	2.5–2.75
R/a	2.5–2.75
κ_{elong}	2.1
δ	0.5
I_p (MA)	5
B_t (T)	5
$\langle n \rangle$ (10^{20} m^{-3})	1
$\langle P_{wall} \rangle$ (MWm^{-2})	0.2
E_b (keV)	500
P_b (MW)	30
P_{ECRH} (MW)	6
P_{Fusion} (MW)	40
H-factor	1.0–1.4
β_N	<3
$f_{non\text{-}ind}$	1
S_{wall} (m^2)	162–188
V_{pl} (m^3)	103–113

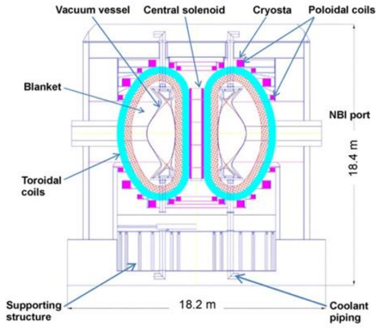


Fig. 4. Basic parameters and schematic drawing of DEMO-FNS.

3.3 China

Along with the achieved and ongoing efforts to establish fusion an energy source, there was a renewed interest in fusion-fission hybrid reactor for energy production, especially based on the progress in the construction and operation of the EAST tokamak in China and the ITER [6]. In recent, three types of hybrid reactor (FDS-EM, -FB and –WT; fusion-driven subcritical reactor-energy multiplier, -fuel breeding, -waste transmutation) were conceptually designed and re-evaluated in China, based on available or very limitedly extrapolated fusion (i.e. a fusion power of 50~500MW) and fission technologies (i.e. Water-cooled PWR or He-cooled HTGR technologies).

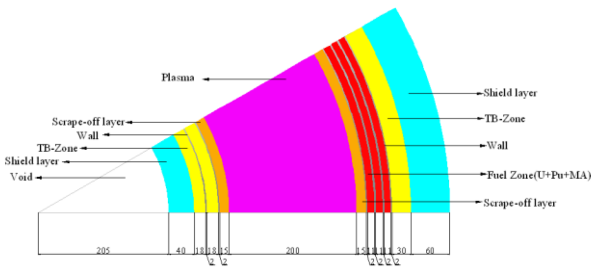


Fig. 5. Radial configuration of FDS-EM in China.

4. Development Strategy of Proto-FFHR in Korea

As an intermediate step between the fission energy application and fusion energy application, the FFHRs can be further utilized as a neutron source for R&D of fusion reactor itself and commercial fusion power plants. The development process of test-FFHR, named a Proto-FFHR, is suggested initially in this article as an alternative and supporting device of future fusion reactors in Korea.

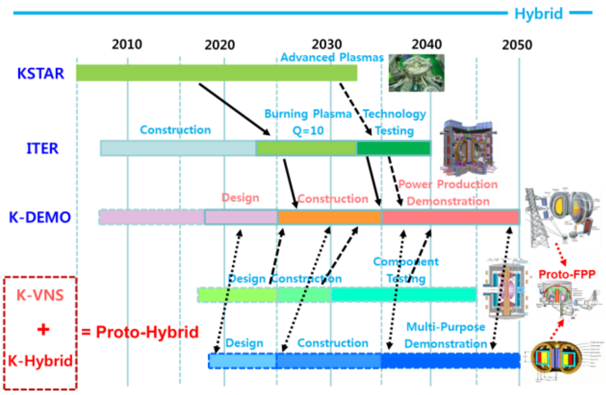


Fig. 6. A (suggested) development roadmap of fusion reactors to fusion power plant in Korea.

5. Conclusions

The development requirement of FFHR in Korea, suggested strongly in this article, can speed up the time for producing energy because of the potential attractiveness of good safety performance and plenty of fuel and easing the requirement of fusion plasma technology (with a low fusion gain Q) and plasma-facing material technology (with a low neutron wall loading).

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